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THE VARIABILITY OF SEYFERT 1.8 AND 1.9 GALAXIES AT 1.6 MICRONS

A. C. Quillen[1], Shanna Shaked, A. Alonso-Herrero, Colleen McDonald, Ariane Lee, M. J. Rieke, & G. H. Rieke
Steward Observatory, The University of Arizona, Tucson, AZ 85721

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ABSTRACT

We present a study of Seyfert 1.5-2.0 galaxies observed at two epochs with the Hubble Space Telescope (HST) at 1.6 microns. We find that unresolved nuclear emission from 9 of 14 nuclei varies at the level of 10-40% on timescales of 0.7-14 months, depending upon the galaxy. A control sample of Seyfert galaxies lacking unresolved sources and galaxies lacking Seyfert nuclei show less than 3% instrumental variation in equivalent aperture measurements. This proves that the unresolved sources are non-stellar and associated with the central pc of active galactic nuclei. Unresolved sources in Seyfert 1.8 and 1.9 galaxies are not usually detected in HST optical surveys, however high angular resolution infrared observations will provide a way to measure time delays in these galaxies.

Subject headings: galaxies: Seyfert — galaxies: nuclei — galaxies: active — infrared: galaxies

1. INTRODUCTION

The discovery that Seyfert 2 galaxies such as can have reflected or polarized broad line emission has led to an approach coined 'unification' towards interpreting the differences between active galactic nuclei (AGNs) in terms of orientation angle (Antonucci 1993). The dusty torus of this unification paradigm absorbs a significant fraction of the optical/UV/X-ray luminosity of an active galaxy and consequently reradiates this energy at infrared wavelengths NGC 1068. As a result of this extinction it is difficult to observe continuum radiation from Seyfert 2 galaxies at optical and UV wavelengths (e.g., Mulchaey et al. 1994). An additional complication is that in a given aperture it may be difficult to identify the percentage of flux from a non-stellar nuclear source (e.g., Alonso-Herrero et al. 1996). For example in Seyfert 2 galaxies much of the nuclear emission may originate from nuclear star formation (e.g., Maiolino et al. 1997; Gonzalez-Delgado & Perez 1993).

The high sensitivity and resolution of near infrared imaging with the Hubble Space Telescope (HST) using NICMOS (the Near Infrared Camera and Multi-Object Spectrograph) allows us to probe galactic centers at wavelengths which experience reduced extinction compared to the optical, and with a beam area about 30 times smaller than is typically achieved with ground-based observations at these wavelengths. This enables us to separate the nuclear emission from that of the surrounding galaxy with unprecedented accuracy. Though a previous survey using WFPC2 at 0.6μm did not detect unresolved nuclear continuum emission from Seyfert 2 galaxies (Malkan et al. 1998), about 60% of the RSA and CfA samples (described below) of Seyfert 1.8-2.0 galaxies display prominent unresolved nuclear sources with diffraction rings in NICMOS images at 1.6μm (McDonald et al. 2000). Though we suspect that these unresolved continuum sources are most likely associated directly with an AGN, they could also be from unresolved star clusters, which are found in a number of normal galaxies (Carollo et al. 1997).

Variability observed in the continuum (e.g., Fitch, Pacholczyk, & Weymann 1967) is an intrinsic property of active galactic nuclei (AGNs) which demonstrates that the energy causing the emission must arise from a very small volume. This led early studies to suggest that accretion onto a massive black hole is responsible for the luminosity (Salpter 1964; Zeldovich & Novikov 1964). Long term multi-year monitoring programs have found that Seyfert 1 galaxies are variable in the near-infrared (Clavel, Wamsteker & Glass 1989; Lebofsky & Rieke 1980), however these programs have only seen a few Seyfert 2 nuclei vary (e.g., Glass 1997; Lebofsky & Rieke 1980). Evidence for variability in the unresolved sources seen in HST

[1]aquillen@as.arizona.edu

observations of Seyfert 2 galaxies would provide evidence that this nuclear emission is non-stellar and so arises from the vicinity of a massive black hole.

2. OBSERVATIONS

In this paper we present a study of variability in Seyfert galaxies. We have searched the HST archive for galaxies (Seyfert and normal) which were imaged *twice* by HST at 1.6μm in the F160W filter with the NICMOS cameras. The Seyfert galaxies with unplanned duplicate observations either satisfy the Revised Shapely-Ames Catalog criterion (described by Maiolino & Rieke 1995) or are part of the CfA redshift survey (Huchra & Burg 1992). The Seyfert observations are discussed in Regan & Mulchaey (1999) and Martini & Pogge (1999) and the observations of the normal or non-Seyfert galaxies are described by Seigar et al. (2000) and Böker et al. (1999). The observations are listed in Table 1 and are grouped by the NICMOS cameras in which they were observed. Images were reduced with the nicred data reduction software (McLeod 1997) using on orbit darks and flats. Each set of images in the F160W filter was then combined according to the position observed. The pixel sizes for the NICMOS cameras are ~ 0.043, 0.076 and $0''.204$ for Cameras 1, 2 and 3 respectively.

At the center of these galaxies we expect contribution from an underlying stellar component in addition to that from an unresolved non-stellar component. To measure the flux from the unresolved component we must subtract a resolved stellar component. However this procedure is dependent upon assumptions made about the point spread function, the form of the stellar surface brightness profile fit to the image and the region over which we fit this profile. This procedure adds uncertainty in the measurement of the unresolved component. However, aperture photometry has proved quite robust with observations of flux calibration standard stars showing variation less than 1% over the lifetime of NICMOS (M. Rieke, private communication 1999). We therefore opt to use aperture photometry to measure flux variations, and then subsequently correct for contamination of the aperture by the background galaxy.

From each pair of images we measure fluxes in apertures of the same angular size. No background was subtracted since the level of background expected at 1.6μm is negligible compared to the galaxy surface brightnesses. Apertures are listed in Table 1 and were chosen so that more than 75% of the flux of an unresolved source would be contained in the aperture. We chose apertures based on which two cameras were used to observe the object. We list in Table 1 the difference divided by the mean of the two flux measurements for each pair of images.

To determine whether the nuclear sources are variable we need to quantify the level of intrinsic scatter in our flux measurements. As a control sample we use the galaxies not identified as Seyfert galaxies and those containing Seyfert nuclei but lacking an unresolved nuclear component. Comparing Camera 2 and Camera 3 measurements for this control sample we find a mean difference of $\mu = -0.9 \pm 0.7\%$ with a variance of $\sigma = 2.0\%$ in the measurements. Comparing measurements with two observations in Camera 2 for this control sample we find a mean difference of $\mu = -0.6 \pm 0.6\%$ with a variance of $\sigma = 1.4\%$. Unfortunately our control sample only contains 2 galaxies with observations in Camera 1 and Camera 2 (MRK 266 and NGC 5929). To supplement this we also measured stars observed in both Camera 1 and 2 in the vicinity of the Galactic Center. Differences in fluxes measured in these 3 image pairs were less than 3%. The statistics of our control sample suggest that the intrinsic scatter of our measurements is smaller than a difference of 3% for all pairs of images. We therefore estimate that flux differences greater than 6% are statistically significant (at $\gtrsim 2\sigma$ level) and likely to be caused by variability and not by scatter in the measurements. The galaxies in which we measure differences larger than this level are listed in Table 2.

We did not find that the unresolved nuclear sources in NGC 404 our NGC 2903 were variable. As demonstrated with UV spectra by Maoz et al. (1998), it is possible that the unresolved component in NGC 404 is from a young star cluster. The same is probably true in NGC 2903 which also contains a compact nuclear source and has a nuclear HII region type spectrum. The scatter in our aperture measurements does not appear to be dependent on the surface brightness profile of the galaxy. No large differences were measured between image pairs for galaxies lacking an unresolved nuclear source.

To estimate the level of variability in the unresolved component we must measure the contribution within the aperture of this component. For each camera we measured a point spread function from stars in the images. We then fit the sum of an exponential bulge profile and the point spread function to the surface brightness profile. The error in this procedure we estimated from the scatter in the residuals and was about $\pm 15\%$ of the total unresolved flux measured. We used the flux from the unresolved component and the shape of the point spread function to estimate the contribution to the flux measured in the apertures listed in Table 1. The differences in the aperture flux measurements are lower limits for differences in the fluxes of the unresolved components (in the limit that the galaxy contributes no flux in

these apertures). The mean unresolved fluxes from the two epochs and extent of variability of the unresolved components (the difference divided by the mean) are listed in Table 2.

3. DISCUSSION

In 9 out of 14 Seyfert 1.5-2.0 galaxies with unresolved components we find a variation greater than 10% in the flux of their unresolved continuum nuclear sources in 2 epochs of observations at 1.6μm. A control sample of Seyfert galaxies lacking unresolved sources and galaxies lacking Seyfert nuclei show less than 3% instrumental variation in equivalent aperture measurements. This suggests that the variability detected is statistically significant at the level of $\gtrsim 2\sigma$. Since we see variations between 0.7-14 month timescales the unresolved sources are probably non-stellar and associated with the central pc of active galactic nuclei. The luminous Seyfert 1 galaxy in our sample, NGC 4151, shows a variation of 10% in its nuclear flux, similar to that seen in the other Seyfert galaxies.

From Table 2 we see that most of the variable sources are Seyfert 1.8 or 1.9 galaxies. NGC 1275, NGC 5033, and NGC 5273 are usually classified as Seyfert 1.9 galaxies though Ho, Filippenko & Sargent (1995) classify them as S1.5. There are two Seyfert 2 galaxies exhibiting variability: MRK 533 and NGC 5347. In MRK 533 a broad component in Paα was detected by Ruiz, Rieke, & Schmidt (1994) and so this galaxy could be classified as a Seyfert 1.9. Seyfert 1.8 and 1.9 galaxies are more likely to display unresolved nuclear sources than Seyfert 2.0 galaxies (McDonald et al. 2000). In the context of the unification model, reduced extinction towards the continuum emitting region at 1.6μm would be expected in Seyfert galaxies which display faint broad line emission. However, this might also suggest that the sizes of the Broad Line Region and 1.6 micron continuum emission region are small compared to the material responsible for the bulk of the extinction.

Two major sources for AGN continuum variability are generally considered: 1) instabilities in an accretion disk (e.g., Shakura & Sunyaev 1973) and 2) jet related processes (e.g., as discussed by Tsvetanov et al. 1998). The second case could be a possible explanation for variability NGC 1275 since it is bright at radio wavelengths and is significantly polarized at optical wavelengths (as discussed by Angel & Stockman 1980). However, the luminosity of the compact nucleus of this galaxy at 1.3 GHz is about 20 times lower than that we measure at 1.6 microns (using the flux from Taylor & Bermeulen). So the 1.6μm flux is higher than what would be expected from synchrotron emission and could be from an additional thermal component (e.g., from hot dust). Better measurements showing the shape of the spectral energy distribution spanning the optical and near-infrared region (to see if two components are present) or a polarization measurement at 1.6μm would help differentiate between a thermal or non-thermal origin for the near-infrared emission.

For the remainder of the Seyferts, their low radio power implies that jet related processes are not responsible for the variability. From observations of the Seyfert 1 galaxy Fairall 9, Clavel et al. (1989) observed large, 400 day, time delays between variations seen at 2 and 3μm and those seen in the UV. Little or no time delay was seen at 1.2μm. This led them to suggest that the longer wavelength emission was associated with hot dust located outside the Broad Line Region (e.g., Lebofsky & Rieke 1980; Barvainis 1987; Netzer & Laor 1993) and that the shorter wavelength emission was reprocessed near the UV emitting region.

For hot dust to cause the 1.6μm emission, dust grain temperatures resulting from absorption of UV radiation must be quite high, nearly that expected for sublimation ($T \sim$ 2000K). The grain temperature should reach this level at a radius $r \sim 0.06\mathrm{pc}\left(\frac{L}{10^{44}\mathrm{erg/s}}\right)^{1/2}$ (following the estimate given in Barvainis 1987). This radius would have a characteristic variability timescale of ~ 70 days or 2 months for a source of 10^{44} ergs/s. We can crudely estimate the bolometric luminosity of our sources from that at 1.6μm (which are listed in Table 2) by assuming a ratio of ~ 10 between the 1.6μm and mid-IR luminosity (e.g, Fadda et al. 1998 for the Seyfert 2s) and a ratio of ~ 10 between the mid-IR and bolometric luminosity (e.g., Spinoglio et al. 1995). The timescales over which we see variations for the brighter sources such as NGC 1275, MRK 533 and UGC 12138 ($L \sim 10^{44}$ ergs/s) are consistent with the 2 month minimum estimated for emission from hot dust. The least luminous of our sources, NGC 4395 ($L \sim 10^{41}$ ergs/s), could have a variability timescale of only a few days for hot dust emitting at 1.6μm, again consistent with the timescale (a few weeks) over which we see a variation.

Emission from hot dust may not necessarily dominate at 1.6μm since the emitting material would require a temperature near the sublimation point of graphites and silicates (Netzer & Laor 1993). However transient super heating at larger radii could still cause emission from hot dust at this wavelength. While the timescales over which we see variability are comparable to those expected from hot dust near a sublimation radius, a long term study comparing flux variations between the near-infrared and X-ray

emission would be needed to determine the exact nature of the 1.6μm emission. This kind of study would also place strong constraints on disk and torus models for the infrared emission (e.g., Efstathiou & Rowan-Robinson 1995; Fadda et al. 1998).

Most of the unresolved nuclear sources studied here exhibit variability. This suggests that most of the many unresolved continuum sources recently discovered in near-infrared surveys (McDonald et al. 2000; Alonso-Herrero et al. 1996) (and not seen in previous optical surveys) are non-stellar and associated with the central pc of an AGN. The near-infrared continuum in low luminosity AGNs can now be studied in a set of objects comprising a larger range of luminosity and orientations. This should provide tests of the unification model for Seyfert 1 and 2 galaxies as well as the nature of accretion in these lower luminosity sources.

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Table 1
Multi Epoch Aperture Photometry of Seyfert and Normal Galaxies at 1.6μm

Galaxy (1)	Type (2)	Nuc. (3)	Prop1 (4)	Date1 (5)	Prop2 (6)	Date2 (7)	Flux1 (8)	Flux2 (9)	Diff% (10)
IC 5063	S2[d]	D	7330/2	25/09/97	7119/2	18/04/97	2.74	2.73	0.57
NGC 1275	S1.9[a]/S1.5[b]	D	7330/2	16/03/98	7457/2	15/08/97	3.74	3.10	19.0
NGC 2460		R	7330/2	28/02/98	7331/2	11/09/97	3.09	3.06	1.06
NGC 2985	T1.9[b]	R	7330/2	18/05/98	7331/2	13/09/97	5.44	5.44	-0.04
NGC 3368	L2[b]	R	7330/2	08/05/98	7331/2	04/05/98	9.23	9.33	-1.10
NGC 2903	H[b]	W	7330/2	22/04/98	7331/2	02/10/97	2.96	3.01	-1.66
NGC 6951	S2[b]	R	7330/2	30/03/98	7331/2	16/12/97	3.88	3.86	0.53
NGC 7177	T2[b]	R	7330/2	15/06/97	7331/2	19/09/97	2.40	2.46	-2.63
MRK 266	S2[a]	R	7867/1	30/04/98	7328/2	13/09/97	1.10	1.07	2.32
MRK 573	S2[a]	D	7867/1	27/08/98	7330/2	26/06/97	2.26	2.20	2.69
NGC 3982	S2[b]	F	7867/1	10/09/98	7330/2	22/06/97	1.36	1.34	1.91
NGC 5033	S1.9[a]/S1.5[b]	D	7867/1	28/04/98	7330/2	19/08/97	5.23	6.31	-8.78
NGC 5252	S1.9[a]	D	7867/1	09/03/98	7330/2	05/04/98	1.81	1.80	0.24
NGC 5273	S1.9[a]/S1.5[b]	D	7867/1	27/05/98	7330/2	03/04/98	2.35	2.57	-8.63
NGC 5347	S2[e]	D	7867/1	06/11/98	7330/2	02/09/97	2.30	2.18	5.45
NGC 5929	S2[a]	R	7867/1	17/07/98	7330/2	21/05/98	1.91	1.90	0.43
MRK 471	S1.8[c]	D	7328/1	16/04/98	7867/1	08/07/97	0.88	0.86	2.06
MRK 533	S2[a]	D	7328/1	13/09/98	7867/1	05/09/97	4.86	5.34	-9.31
UGC 12138	S1.8[a]	D	7328/1	09/09/98	7867/1	28/07/97	3.60	4.23	-16.0
UM 146	S1.9[a]	D	7328/1	03/08/98	7867/1	13/09/97	1.36	1.46	-6.89
NGC 1241	S2[f]	W	7330/2	18/03/98	7919/3	19/06/98	4.24	4.24	0.01
NGC 214		R	7330/2	29/05/98	7919/3	09/06/98	2.73	2.67	2.13
NGC 2639	S1.9[b]	R	7330/2	23/02/98	7919/3	07/06/98	7.25	7.27	-0.29
NGC 2903	H[b]	W	7330/2	22/04/98	7919/3	09/06/98	5.31	5.28	0.45
NGC 3627	T2[b]	R	7330/2	22/04/98	7919/3	04/06/98	14.99	15.59	-3.89

Table 1 continued

NGC 404	L2[b]	D	7330/2	02/03/98	7919/3	19/01/98	11.74	11.64	0.84
NGC 4151	S1.5[b]	D	7215/2	22/05/98	7806/3	14/10/97	97.35	108.99	-11.3
NGC 4258	S1.9[b]	W	7330/2	21/11/97	7919/3	09/06/98	19.20	18.84	1.86
NGC 4395	S1.8[b]	D	7330/2	17/05/98	7919/3	07/06/98	1.14	1.02	11.2
NGC 5128	S2[g]	D	7330/2	17/09/97	7919/3	17/06/98	16.27	16.72	-2.72
NGC 628		W	7330/2	15/06/97	7919/3	30/01/98	1.37	1.40	-2.42
NGC 6744	L[h]	R	7330/2	09/09/97	7919/3	11/06/98	7.03	7.18	-2.08
NGC 6946	H[b]	R	7330/2	18/05/98	7919/3	19/01/98	13.73	13.99	-1.86

Note.— Seyfert and normal galaxies have been grouped by the NICMOS cameras in which they were observed. The first group consists of Camera 2/Camera 2 pairs, the second Camera 1/Camera 2 pairs, the third Camera 1/Camera 1 pairs and the last group Camera 2/Camera 3 pairs. Columns: (1) Galaxy; (2) Classification of emission lines in the nucleus. References are denoted with superscripts: [a]=Osterbrock & Martel (1993), [b]=Ho, Filippenko & Sargent (1995a,b) (classifications from these works include H = HII nucleus, S = Seyfert nucleus, L = LINER and T = transition object with numbers corresponding to subtypes), [c]=Dahari, & De Robertis (1988), [d]=A polarized broad line component was detected in IC 5063 by Inglis et al. (1993), [e]=Huchra & Burg (1992). No data are available about the line ratios of NGC 5347, [f]=Dahari (1985), [g]=Tadhunter et al. (1993), Spectroscopic identifications for the nuclei of NGC 2460 and NGC 214 could not be found. The nucleus of NGC 628 lacks emission lines (Ho et al. 1995a), [h]= NGC 6744 was classified as a LINER by Vaceli et al. (1997) and no subtype was given; (3) Type of nucleus seen in the F160W images. When the nucleus displayed a clear diffraction ring we denote 'D', when the ring was faint we denote 'F', and when the galaxy was resolved we denote 'R'. When there was an unresolved peak but no sign of a diffraction ring we denote 'W'; (4) Proposal ID number followed by camera number of the first NICMOS image considered; (5) Date that this image was observed; (6) Proposal ID number followed by camera number of the second NICMOS image considered; (7) Date that this image was observed; (8) Nuclear flux at 1.6μm measured in mJy for the image identified by columns 4 and 5. For the galaxies observed in Camera 1 and 2 we used an aperture of $0''.602$ in diameter. For the galaxies observed solely in Camera 1 the aperture was $0''.602$. For the galaxies observed solely in Camera 2 the aperture was $0''.760$. For the galaxies observed in Camera 2 and 3 the aperture was $1''.216$; To convert these fluxes into mJy we used conversion factors 2.360×10^{-3}, 2.190×10^{-3}, 2.776×10^{-3} mJy per DN/s for Cameras 1, 2 and 3 respectively. This flux calibration is based on measurements of the standard stars P330-E and P172-D during the Servicing Mission Observatory Verification program and subsequent observations (M. Rieke 1999, private communication); (9) Flux in an aperture for the image identified by columns 6 and 7; (10) Percent difference divided by the mean of the fluxes listed in columns 7 and 8.

Table 2
Variable Unresolved Nuclear Sources

Galaxy (1)	Type (2)	$v_{\rm helio}$ km/s (3)	size pc (4)	flux mJy (5)	var % (6)	time months (7)	$L_{1.6}\mu$m ergs/s (8)
NGC 1275[a]	S1.9/S1.5	5264	34	3.20	20	7.0	3.3e42
NGC 5033	S1.9/S1.5	875	6	2.41	45	8.3	7.0e40
NGC 5273	S1.9/S1.5	1089	7	1.22	18	1.8	5.4e40
MRK 533	S2[b]	8713	56	3.59	13	14.1	1.0e43
NGC 5347	S2	2335	15	1.08	11	12.3	2.2e41
UGC 12138	S1.8	7375	48	2.25	28	13.4	4.6e42
UM 146	S1.9	5208	33	0.60	17	10.7	6.1e41
NGC 4395[c]	S1.8	319	1.3	0.83	15	0.7	1.2e39
NGC 4151	S1.5	995	6.5	103	11	7.3	3.8e42

[a]Variation in the nuclear flux of NGC 1275 was reported previously by Lebofsky and Rieke (1980).

[b]In MRK 533 a broad component in Paα was detected by Ruiz, Rieke & Schmidt (1994).

[c]NGC 4395 has been labelled ‘the least luminous Seyfert 1 galaxy’ (Filippenko & Sargent 1989; Filippenko, Ho, & Sargent 1993). The flux at 4400$\AA$ has varied by a factor of three in just one month (Lira et al. 1999), so a variation of 15% in a few weeks at 1.6μm is not surprising.

Note.— The Seyfert galaxies with unresolved sources which did not vary significantly between observations were IC 5063, MRK 573, NGC 5252, MRK 471 and NGC 5128. Columns:- (1) Seyfert Galaxy; (2) Seyfert type; (3) Heliocentric velocity; (4) Physical size corresponding to $0''.1$. These have been estimated using a Hubble constant of 75 km s^{-1} Mpc^{-1} except in the case of NGC 4395 for which we adopt a distance of 2.6 Mpc (Rowan-Robinson 1985); (5) The flux of the unresolved component (galaxy subtracted) averaged between the two measurements. We estimate the error to be $\sim \pm 15\%$ of the flux listed; (6) Percent variation (absolute value of the difference divided by the mean) of the unresolved component; (7) Time between the two different observations; (8) Mean luminosity at 1.6μm estimated by νf_ν.